

Low Temperature Creep of a Titanium Alloy Ti-6Al-2Cb-1Ta-0.8Mo

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1997

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Abstract

This paper presents a methodology for the analysis of low temperature creep of titanium alloys in order to establish design limitations due to the effect of creep. The creep data on a titanium Ti-6Al-2Cb-1Ta-0.8Mo are used in the analysis. A creep equation is formulated to determine the allowable stresses so that creep at ambient temperatures can be kept within an acceptable limit during the service life of engineering structures or instruments. Microcreep which is important to design of precision instruments is included in the discussion also.

Introduction

Titanium alloys have the intrinsic property of creep at ambient temperatures. Previous work has shown that commonly used alloys such as Ti-6Al-4V would creep at stress levels below yield strength at room temperature (1). This work is to study creep of a titanium alloy in a range of low temperatures that may exist both in low Earth orbit and in hydrospace environment. The material tested was titanium alloy Ti-6Al-2Cb-1Ta-0.8Mo (Ti-6211). Chu (2) has studied creep and stress relaxation of this alloy at room temperature. The alloy has been developed for marine applications with excellent weldability, fracture toughness, and stress corrosion resistance (3, 4). It should be also suitable for space and other applications where such properties are at a premium.

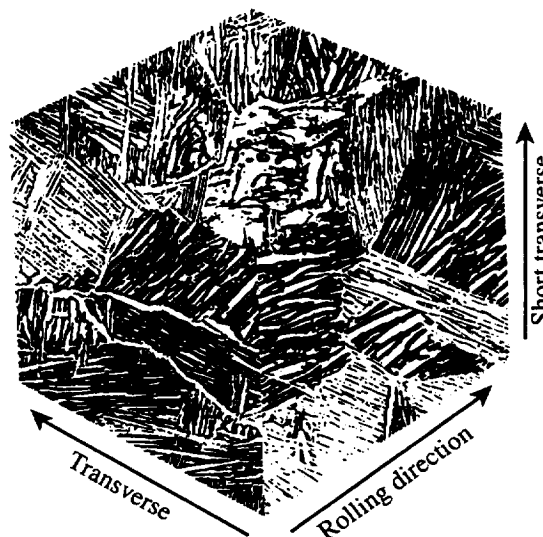


Figure 1. Photomicrograph of Ti-6211 Rolled Plate

Experimental Procedure

Material and Specimens

The material studied (Ti-6211) was a near-alpha titanium alloy. It was fabricated to a 51 mm thick plate by commercial mill process with standard chemical composition (5). Figure 1 shows that the alloy had medium to coarse Widmanstätten alpha microstructure and large prior beta grains. Mechanical properties are listed in Table 1. Specimens were cut in the longitudinal direction of the plate. The finished specimens had a diameter of 7.4 mm in a gage length of 57.2 mm.

Table 1. Tensile Properties of Ti-6211

Temperature	Yield Strength 0.2% Offset	Tensile Strength	Elongation	Reduction in Area
°C	MPa	MPa	%	%
0	753.6	836.3	9.50	23.87
0	766.7	843.2	11.25	24.71
25	717.7	812.2	10.50	23.47
25	723.3	805.3	13.50	21.86
50	690.2	774.3	10.50	27.25
50	681.9	772.9	12.50	24.67
150	559.9	671.5	11.00	28.50
150	570.9	675.0	11.50	27.97

Creep Tests

Tensile creep tests were conducted at 0 °C, 25 °C, and 50 °C. The specimens were tested in lever frames where dead weights were loaded in large increments. Creep strains were measured by an extensometer with optical instrumentation.

Results and Discussion

Creep Behavior

The creep stresses and strains of 18 specimens tested at the three temperatures are summarized in Table 2. The data show that temperature has a significant effect on the creep properties of the Ti-6211 alloy. For instance, under the load of 689.5 MPa at 0 °C the alloy had 0.95% creep in 1007 hours. When the temperature was 25 °C, creep was increased over four times to 4.59% under the same stress for the same length of time. Furthermore, the specimen would break shortly after loading at the stress level of 655.0 MPa when tested at 50 °C.

Table 2. Summary of Creep Data on Ti-6211

Temperature	Creep Stress	Test Duration	Total Creep
°C	MPa	Hour	%
0	620.5	772 ⁽¹⁾	0.31
0	655.0	1010	0.56
0	689.5	1007	0.95
0	717.1	1013	2.98
0	730.8	476.6 ⁽²⁾	-
25	586.1	1009	0.35
25	620.5	1008	0.51
25	655.0	1004	3.11
25	689.5	1007	4.59
25	717.1	451 ⁽²⁾	-
50	482.6	1006	0.11
50	571.1	1007	0.16
50	551.6	1009	0.40
50	586.1	96 ⁽¹⁾	0.48
50	586.1	1011	0.52
50	620.5	1007	2.49
50	655.0	60 ⁽²⁾	-
50	717.1	1 ⁽²⁾	-
150	586.1	11 ⁽²⁾	-

Note:

(1) Test terminated because of power failure

(2) Specimen broke during testing

Examples of creep strain-time data are shown in Figures 2 and 3. The data exhibit the general characteristics of transient or primary creep with strain rate decreasing quickly at low stresses and gradually at high stresses. As the creep rate is ever diminishing with time, the data of each specimen tend to level off eventually. The transient nature of creep at low temperatures has been explained in terms of an exhaustion process; and the theory has established a logarithmic law, which dictates that creep strain should vary linearly with the logarithm of time (6, 7). McLean (7) has reviewed previous work in support of this law. He concluded that the creep strains are relatively small and fairly insensitive to changes in stress. However, the logarithmic law has been found inadequate for the present analysis. The data of two tests are shown in Figure 4 in a semilog plot. While the data of low strain values obtained at 0 °C can be faired by a straight line, those of high values at 50 °C have definitely deviated from the logarithm law. Also, the results in Table 2 indicate that a small change in stress could create a large change in creep. At 25 °C, for example, the alloy had 0.51% creep under 620.5 MPa stress; when the stress was increased about 11% to 689.5 MPa, the creep strain had a ninefold increase to 4.59% in 1007 hours.

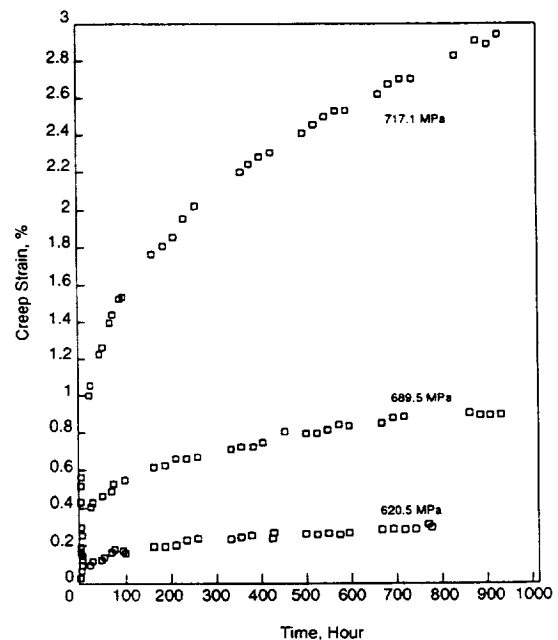


Figure 2. Typical creep data at 0 °C

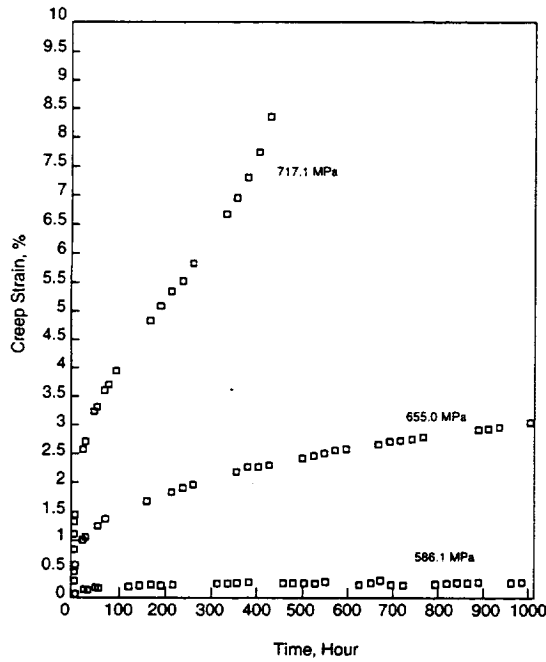


Figure 3. Typical creep data at 25 °C

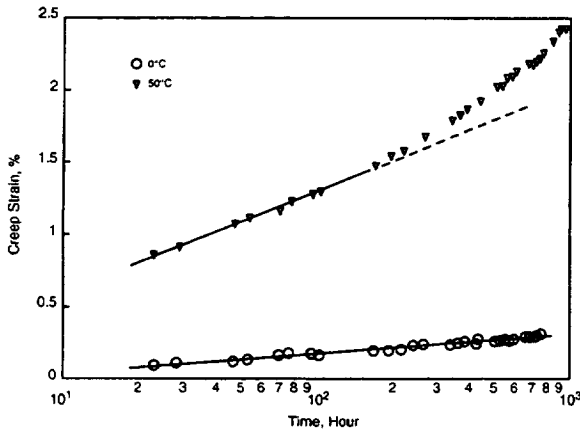


Figure 4. Semi-log plot of creep data, stress = 620.5 MPa

According to Lubahn and Felgar (8), creep of metals often follows a power function with the strain-time curves being linear in log-log coordinates. The present data are so plotted in Figures 5 –7. For each temperature, the data for the individual stress levels can be faired into linear and parallel curves. The only exceptions are found in Figures 5 and 6, where a few data points fall out of the linear curves for stress values of 730.8 MPa and 717.1 MPa at 0 °C

and 25 °C, respectively. However, these data were taken just before the specimens ruptured in the tests; and therefore they are not expected to follow the general trend of the creep data. Thompson and Odegard (9) has shown that log-log plots of creep data on a titanium alloy Ti-5Al-2.5Sn are linear up to 10,000 hours. Thus, the creep strain, ϵ , is related to time, t , by a power function:

$$\epsilon = At^c \quad (1)$$

Chu (2) has shown that the quantity A depends on Stress, S , such that

$$A = aS^b \quad (2)$$

By combining these two equations, the overall creep behavior of the Ti-6211 alloy can be described by

$$\epsilon = aS^bt^c \quad (3)$$

In this work, the values of the constants a , b , and c are determined by the creep results for the three temperatures, as follows:

$$0^\circ\text{C} \quad \epsilon = \left(\frac{S}{759.485} \right)^{15.190} t^{0.275} \quad (4)$$

$$25^\circ\text{C} \quad \epsilon = \left(\frac{S}{708.471} \right)^{14.750} t^{0.266} \quad (5)$$

$$50^\circ\text{C} \quad \epsilon = \left(\frac{S}{665.344} \right)^{13.940} t^{0.256} \quad (6)$$

Where

ϵ = creep strain, %

S = creep stress, MPa

t = time, h

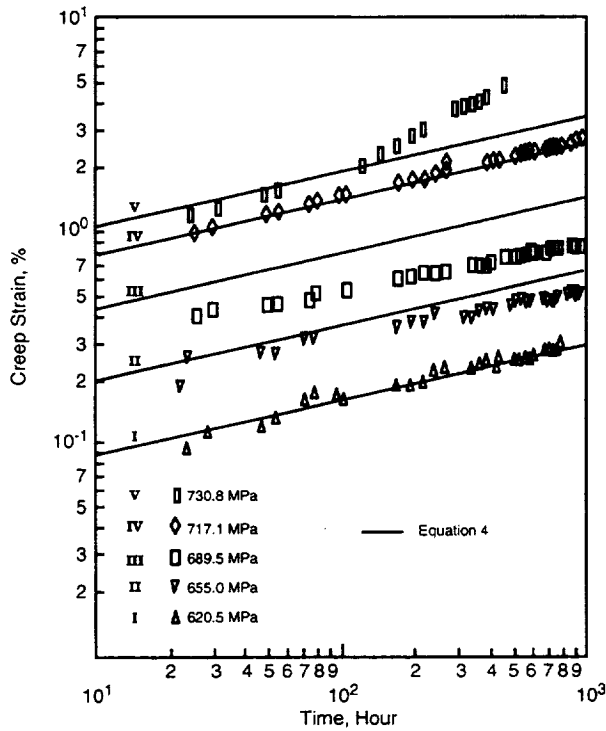


Figure 5. Creep data at 0 °C

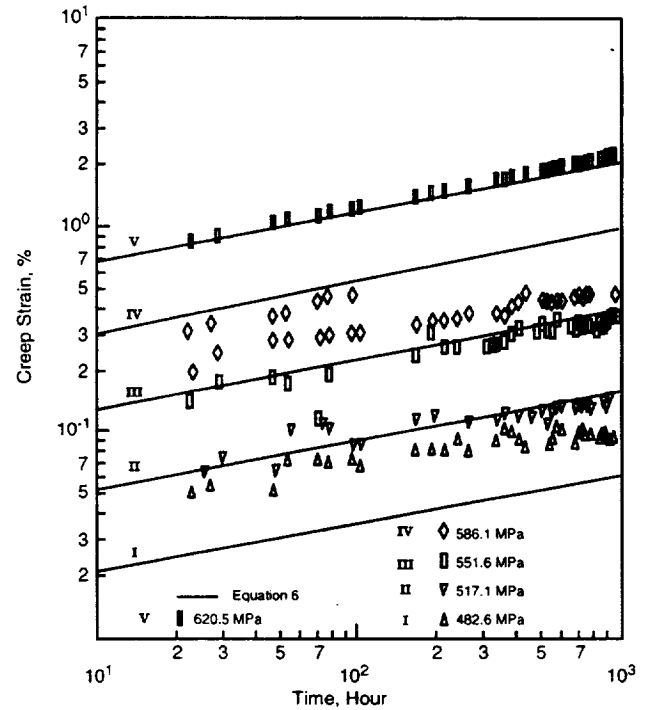


Figure 7. Creep data at 50 °C

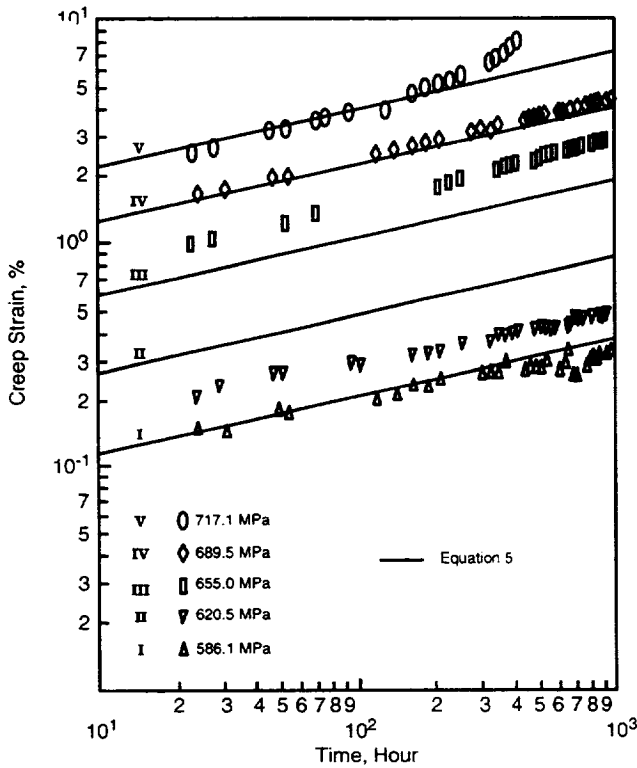


Figure 6. Creep data at 25 °C

Creep curves computed by Equations 4–6 are drawn in Figures 5–7 to compare with the experimental data. Although the curves do not coincide exactly with the data at every stress level, the overall accuracy of the equations is quite satisfactory, since the discrepancies can be considered as normal scatter of data. It is interesting to note that, at 50 °C, one test at 586.1 MPa was discontinued prematurely because of power failure (Table 2); and a duplicate test was then conducted until 1011 hours. The differences in creep strains for the same duration obtained by these two tests at identical stress level are about 0.1% (Figure 7) which is attributable to experimental error and material inhomogeneity. This magnitude of difference is similar to that between the theoretical curves and the test data.

Temperature Effects

The effect of temperature can be seen through a consideration of strain rate, $\dot{\epsilon}$. By differentiating Equation 1 with respect to t , the strain rate is obtained:

$$\dot{\epsilon} = \frac{C\epsilon}{t} \quad (7)$$

Combining Equation 7 with Equation 3, the expression of creep behavior can be changed to the following form:

$$S = K\epsilon^m\dot{\epsilon}^n \quad (8)$$

Where K = strength coefficient
 m = strain hardening exponent
 n = strain rate exponent

For the three test temperatures Equation 8 becomes

$$0^\circ\text{C} \quad S = 777.494\epsilon^{0.048}\dot{\epsilon}^{0.018} \quad (9)$$

$$25^\circ\text{C} \quad S = 725.590\epsilon^{0.050}\dot{\epsilon}^{0.018} \quad (10)$$

$$50^\circ\text{C} \quad S = 628.202\epsilon^{0.053}\dot{\epsilon}^{0.018} \quad (11)$$

where $\dot{\epsilon}$ = strain rate, % per hour

It is interesting to note that, from 0°C to 50°C , the strain hardening exponent has a slight increase with an average value of 0.050 and the strain rate exponent is a constant equal to 0.018. It shows that an increase in strain rate, for example, by a factor of 10 would cause a corresponding increase in stress only by a factor of 1.04. This is a small effect and is characteristic of strong metals at low temperatures. Through Equations 9–11, the effect of temperature is seen by the change in strength coefficient, i.e., an increase in temperature caused a decrease in strength coefficient values, and therefore a decrease in strength of the alloy.

Creep of metals has been studied as a thermally activated process, and the dependence of creep on temperature can be described by a rate equation (6):

$$\dot{\epsilon} = \dot{\epsilon}_0 \exp\left(-\frac{\Delta H}{RT}\right) \quad (12)$$

where $\dot{\epsilon}_0$ = pre-exponential factor
 ΔH = activation energy for creep
 R = universal gas constant
 T = absolute temperature

The above equation has been commonly used to determine activation energy for creep by conducting creep test with incremental change in temperature (6). A different method is used in this work. Equation 12 states that a plot of $\log \dot{\epsilon}$ versus $1/T$ should be a linear curve with a negative slope, which is realized by the present data (Figure 8). Usually $\dot{\epsilon}$ is the steady state creep rate. In this analysis, the creep rates at constant values of creep strains are used. The creep rates in Figure 8 are calculated from Equations 9, 10, and 11. The values of creep strains and stresses used in the calculations are arbitrarily chosen.

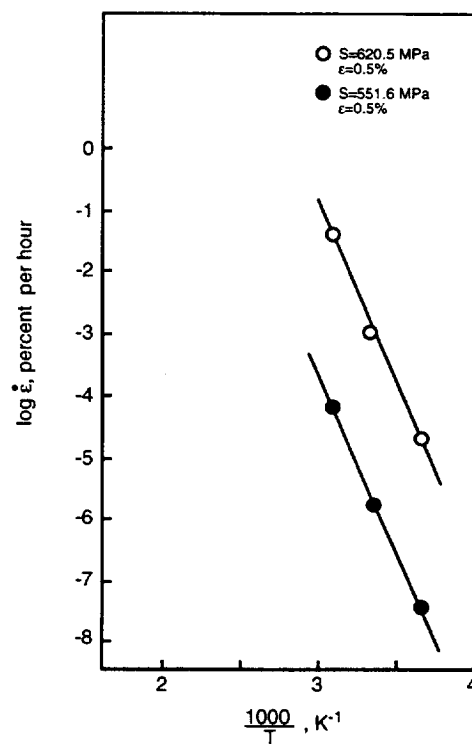


Figure 8. Log of creep rate versus the inverse of temperature

By Equation 12, the activation energy for creep can be calculated from the slope of the curves in Figure 8 for Ti-6211 as $\Delta H = 113 \text{ kJ/mol}$. Since the two curves are parallel the activation energy is independent of stress. Kramer and Balasubramanian (10) have obtained $\Delta H = 117 \text{ kJ/mol}$ for a Ti-6Al-4V alloy at 288°C – 343°C . The two values of activation energy for creep can be considered identical.

It is important to note that Libanati and Dymant (11) have determined the activation energy for self diffusion in alpha titanium as 123 kJ/mol at 690 °C–850 °C. These activation energy values are practically the same. This is consistent with the correlation between creep and self diffusion established by Dorn and Sherby for various metals (12, 13). It indicates that creep of alpha titanium alloys, including Ti-6211, involves a single, diffusion-controlled process at 0 °C–850 °C.

The temperature effects on creep can be expressed by a temperature-compensated time parameter (12, 13) defined as

$$\theta = t \exp\left(-\frac{\Delta H}{RT}\right) \quad (13)$$

The creep strains for different temperatures can be brought into coincidence under the same stress when plotted against this parameter. Examples are given in Figure 9 where the creep data for 0 °C, 25 °C, and 50 °C are faired into linear and parallel curves in terms of θ in log-log coordinates. Thus, the overall creep behavior of Ti-6211 can be described by an expression in the form of Equation 3 by substituting the parameter θ for time, t . All of the present data for different temperatures and stresses are represented in this way by a single equation, as follows:

$$\varepsilon = \left(\frac{S}{318.179}\right)^{14.815} \left[t \exp\left(-\frac{13500}{T}\right)\right]^{0.260} \quad (14)$$

Where

ε = creep strain, %
 S = creep stress, MPa
 t = time, h
 T = absolute temperature, K .

The calculated results of Equation 14 are compared with experimental data in Figures 10–12. The accuracy of the equation is considered satisfactory; it is about the same as that of Equations 4–6 established for the individual temperatures.

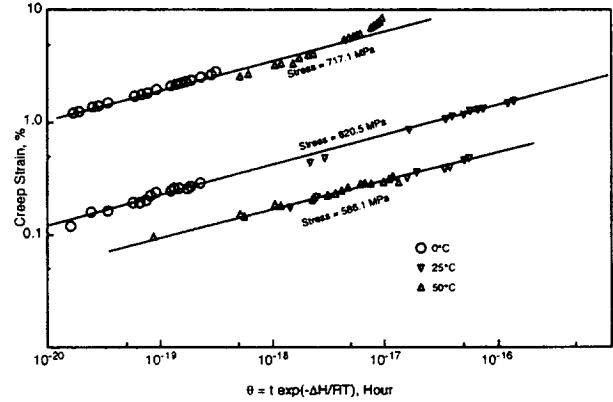


Figure 9. Creep strain versus the temperature-compensated time parameter, θ

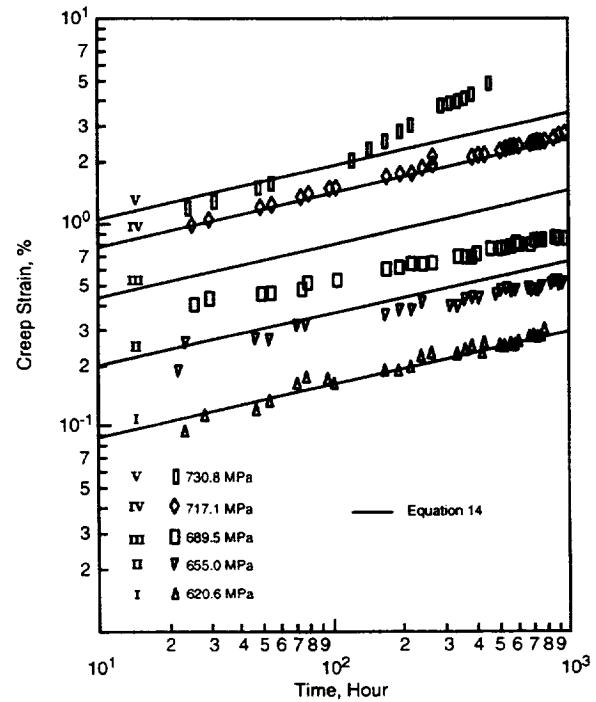


Figure 10. Creep data at 0 °C

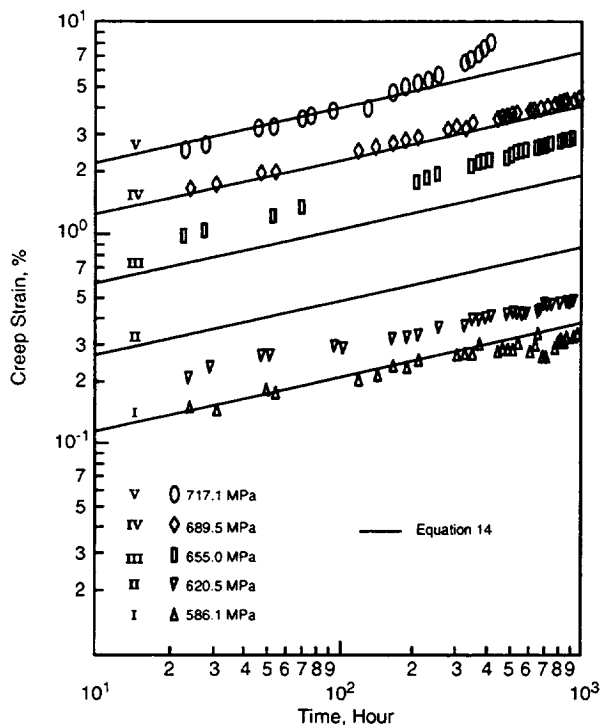


Figure 11. Creep data at 25 °C

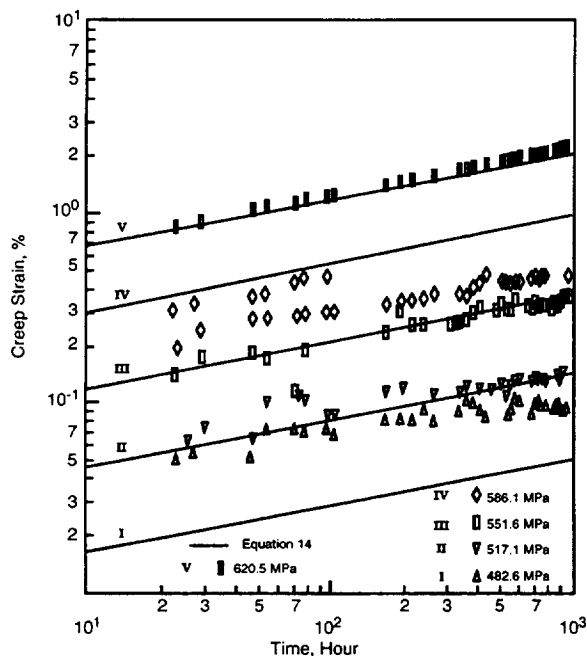


Figure 12. Creep data at 50 °C

It should be pointed out that Equations 12 and 13 and the correlation between creep and diffusion have been considered applicable only at high temperatures. However, the present results show that

they are applicable to low temperature creep of Ti-6211 as well. Furthermore, based on the foregoing discussion of activation energy for creep and self diffusion, it is reasonable to expect that Equation 14 should be useful in a wide range of temperatures.

Creep Strength and Rupture

The creep strength of an alloy at a certain temperature is not a fixed value due to variations in definition or design considerations. In principle, it is the stress suitable for a particular engineering application, such that the strain will be acceptably small during service life of the structure. In the present discussion, the creep strength of the tested alloy can be determined as the stress for 1.00 per cent creep in 100,000 hours. Equations 4–6 and Equation 14 can be used to calculate the creep strength values. Marschall and Maringer (14) have discussed other cases where dimensional stability is so restricted that only a limited amount of microcreep is permitted. Then the above equations can be used for an extrapolation to estimate the allowable load stress. Following their example, the microcreep strength is calculated for 1×10^{-6} creep strain in 1000 hours. The creep strength values are listed below:

Temp °C	Creep Strength, MPa		Microcreep Strength, MPa	
	Eq. 4–6	Eq. 14	Eq. 4–6	Eq. 14
0	616.3	619.2	364.8	360.5
25	575.6	575.7	335.0	335.2
50	538.5	541.4	302.7	315.2

Comparing with the tensile properties (Table 1), it can be seen that the creep strength is about 80% of the yield strength of the alloy at all three temperatures. This is equivalent to using a factor of safety of 1.25, which is often used in design for space and other advanced applications. This illustrates that creep of Ti-6211 is unlikely to be a problem if the usual design procedure is used for low temperature applications. However, when microcreep is an important concern, structural members made of the alloy should not be stressed over 46% of the yield strength at the three temperatures so as to keep dimensional changes on the order of part per million for a long lifetime of service.

Four specimens broke during creep testing (Table 2). The data on these specimens indicate that Ti-6211 could fail by creep rupture if the load stress is near its yield strength level. This raises an important question whether the alloy would fail prematurely at lower stresses also. For example, it is desirable to know if rupture would occur at a stress, say, equal to the creep strength within the assumed service life of 100,000 hours. The present data may be examined to obtain some useful information on the rupture behavior of the alloy. For this purpose, an additional specimen was tested at 150 °C under a creep stress of 586.1 MPa; the specimen ruptured in 11 hours.

Results of the five ruptured specimens are used to construct a master curve in terms of the Larson-Miller parameter (15), as follows:

$$P = 1.8 T (\log t + c) \quad (15)$$

Where

T = absolute temperature, K
t = rupture time, h
c = 20

In the above equation, the term c is a constant; the usual value of 20 is used to construct the master curve shown in Figure 13. By a very short extrapolation, the plot shows that, at 25 °C, Ti-6211 should have a rupture time of about 3×10^{10} hours when the stress is equal to the creep strength of 575.7 MPa. Also, the rupture time is about 1×10^{10} hours when the stress is equal to the creep strength of 540 MPa at 50 °C. Although the data base is not extensive, the calculations simply demonstrate that the Ti-6211 alloy is unlikely to fail by creep rupture when used at the usual design stress level at low temperatures.

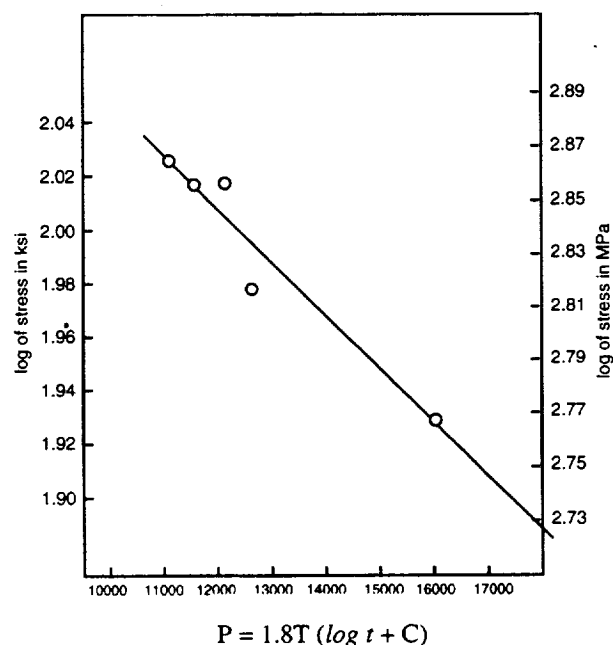


Figure 13. Larson-Miller Plot of Rupture Data

Conclusions

Creep data on the Ti-6211 alloy obtained at the three test temperatures warrant the following conclusions:

1. The alloy creeps at low temperatures with characteristics of primary creep. The strain-time relation follows a power function.
2. Temperature has a noticeable effect on strength; an increase in temperature causes a decrease in strength. The strain hardening exponent has slightly higher values with increasing temperature, whereas the strain rate exponent remains at a constant value.
3. The correlation of activation energy for creep and self diffusion indicates that creep involves a single diffusion-controlled mechanism from low to high temperatures.

4. Creep data for all the test stresses and temperatures can be represented by a simple equation through the use of a temperature-compensated time parameter.

5. Creep and creep rupture are unlikely to be a problem for engineering applications at low temperatures.

Acknowledgement

The experimental work of this investigation was completed at the Naval Surface Warfare Center Carderock Division.

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REPORT DOCUMENTATION PAGEForm Approved
OMB No. 0704-0188

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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE January 1997	3. REPORT TYPE AND DATES COVERED Technical Memorandum	
4. TITLE AND SUBTITLE Low Temperature Creep of a Titanium Alloy Ti-6Al-2Cb-1Ta-0.8Mo			5. FUNDING NUMBERS Code 313	
6. AUTHOR(S) H. P. Chu				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Materials Engineering Branch Goddard Space Flight Center Greenbelt, Maryland 20771			8. PERFORMING ORGANIZATION REPORT NUMBER 97B00021	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Goddard Space Flight Center National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER TM-104641	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Category: 24 This report is available from the NASA Center for Aerospace Information, 800 Elkridge Landing Road, Linthicum Heights, MD 21090; (301) 621-0390			12b. DISTRIBUTION CODE	
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14. SUBJECT TERMS Titanium alloy, creep, low temperature			15. NUMBER OF PAGES 9	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited	